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14. ABSTRACT

New framework for terrain evolution analytics based on time series of point cloud elevation data was developed and implemented in open source GIS. The framework introduced new terrain dynamics metrics that fully captures spatial and temporal variability of elevation surface change due to natural processes and human activities. The framework includes novel, robust techniques for processing time series of lidar point clouds with diverse properties into consistent representation of terrain evolution within space-

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Report Title

Terrain Dynamics Analysis Using Space-Time Domain Hypersurfaces and Gradient Trajectories Derived From Time Series of 3D Point Clouds

ABSTRACT

New framework for terrain evolution analytics based on time series of point cloud elevation data
was developed and implemented in open source GIS. The framework introduced new terrain dynamics metrics that fully captures spatial and temporal variability of elevation surface change
due to natural processes and human activities. The framework includes novel, robust techniques for processing time series of lidar point clouds with diverse properties into consistent representation of terrain evolution within space-time cube. Unique visualizations of modeled surface evolution were then generated by extracting and analyzing contour evolution isosurfaces. Surface gradient evolution in space-time cube was also investigated and topological relationships between the elevation and gradient hyper surface fields were explored. Evolution of second order space-time topographic parameters revealed high sensitivity to noise and need for further development of optimized space-time interpolation method. Tangible geospatial modeling system was further developed to support the analysis of changing elevation surfaces in controlled environment.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/13/2012	1.00	Michael J. Starek , Helena Mitasova, Eric Hardin, Katherine Weaver, Margery Overton, Russell S. Harmon. Modeling and analysis of landscape evolution using airborne, terrestrial, and laboratory laser scanning, Geosphere, (12 2011): 1340. doi:
07/31/2015	9.00	Paul Paris, Helena Mitasova. Barrier Island Dynamics Using Mass Center Analysis: A New Way to Detect and Track Large-Scale Change, ISPRS International Journal of Geo-Information, (01 2014): 49. doi: 10.3390/ijgi3010049
08/14/2012	4.00	Helena Mitasova, Russell S. Harmon, Katherine J. Weaver, Nathan J. Lyons, Margery F. Overton. Scientific visualization of landscapes and landforms, Geomorphology, (01 2012): 122. doi: 10.1016/j.geomorph.2010.09.033
08/14/2012	3.00	Eric Hardin, M. Onur Kurum, Helena Mitasova, Margery F. Overton. Least Cost Path Extraction of Topographic Features for Storm Impact Scale Mapping, Journal of Coastal research, (07 2012): 970. doi: 10.2112/JCOASTRES-D-11-00126.1
08/18/2013	6.00	S. Thakur, H. Mitasova, E. Hardin, E. Russ, B. Blundell, L. Tateosian. Visualizations of coastal terrain time series, CMC: Computers, Materials & Continua, (05 2013): 0. doi: 10.1177/1473871613487086
08/18/2013	7.00	M. J. Starek, H. Mitasova, K. W. Wegmann, N. Lyons. Space-Time Cube Representation of Stream Bank Evolution Mapped by Terrestrial Laser Scanning, IEEE GEOSCIENCE AND REMOTE SENSING LETTERS, (05 2013): 0. doi: 10.1109/LGRS.2013.2241730
08/18/2013	8.00	Eric Hardin, Margery Overton, Sidharth Thakur, Laura Tateosian, Helena Mitasova. SUMMARY VISUALIZATIONS FOR COASTAL SPATIAL-TEMPORAL DYNAMICS, , (01 2013): 241. doi: 10.1615/Int.J.UncertaintyQuantification.2012003969

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(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Mitasova, H., Stepinski, T., Jasiewicz, J., Neteler, M., Gebbert, S. AGU 2014. Analysis of Giga-size Earth Observation Data in Open Source GRASS GIS 7 - from Desktop to On-line Solutions. AGU Fall Meeting 2014, December 15th-19th, San Francisco, California, USA.

*Petrasova, A., Brendan *Harmon, Helena Mitasova and Jeffrey White, Tangible Exploration of Subsurface Data, AGU Fall Meeting 2014, December 15th-19th, San Francisco, California, USA.

*Petrasova, A., *Harmon, B., Mitasova, H, GIS-based modeling with tangible interaction, FOSS4G 2014, Portland, OR, Sep. 2014

Petras, V., Petrasova, A., Mitasova, H., FOSS4G 2014. Spatio-temporal data visualization in GRASS GIS: desktop and web solutions, FOSS4G, Portland, Oregon, Sep. 2014

Petrasova, A., Harmon, B., Petras, V., Mitasova, H., iEMSs 2014. GIS-based environmental modeling with tangible interaction and dynamic visualization.

Mitasova H., *Harmon B., and Blundell S.B., Exploring topographic change impacts on land surface processes using tangible interface, invited talk at the GSA Annual meeting, Denver, October 2013

Mitasova H; M.J. Starek; *E.J. Hardin; K.W. Wegmann; B.S. Blundell, Space-Time Cube Analytics of Evolving Landforms Captured by Airborne and Terrestrial Lidar, invited talk at AGU Fall meeting 2012

Mitasova H; *E.J. Hardin; *A. Kratochvilova; M. Landa, From Particles and Point Clouds to Voxel Models: High Resolution Modeling of Dynamic Landscapes in Open Source GIS, invited talk at AGU Fall meeting 2012

*Lyons, N.J., Mitasova H., Starek M.J.; Wegmann, K.W., Terrestrial Laser Scanning of a Stream Bank During Naturally and Experimentally Induced Erosion by Groundwater Seepage,?poster AGU Fall 2012

Starek MJ, H. Mitasova, K. Wegmann, *N. Lyons, *K. Cepero, Spatiotemporal Representation of Stream Bank Evolution Mapped by Terrestrial Laser Scanning, talk, AGU Fall 2012

*Hardin E, Mitas L, Mitasova H., Simulation of Wind-Blown Sand for Geomorphological Applications: A Smoothed Particle Hydrodynamics Approach, GSA 2012

*Russ, E. Mitasova, H., Time series and space-time cube analyses on North Carolina Outer Banks, GSA 2012

Starek MJ, Mitasova H., *Hardin E., Bundell B., Gibeaut J., Radosavljevic B., Lord A. Space-Time Elevation Cube for Visualization of Landscape Dynamics with Lidar Time Series Data, JALBTCX 2012, Chicago, 2012.

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
05/23/2013	5.00	Michael J. Starek, Russell S. Harmon, Helena Mitasova. Fort Fisher, NC Past and Present: A Geospatial Analysis using LiDAR and GIS, Proc. 9th International Military Geosciences Conference.. 19-JUN-11, . : ,

TOTAL: 1

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
07/13/2012	2.00	Helena Mitasova , Eric Hardin , Michael J. Starek , Russell S. Harmon, Margery F. Overton. Landscape dynamics from LiDAR data time series, Geomorphometry 2011. 07-SEP-11, . : ,
07/31/2015	10.00	Anna Petrasova, Brendan Harmon, Vaclav Petras, Helena Mitasova. GIS-based environmental modeling with tangible interaction and dynamic visualization, 7th International Congress on Environmental Modelling and SoftwareSan Diego, California,. 15-JUN-14, . : ,
07/31/2015	12.00	Vaclav Petras, Helena Mitasova, Anna Petrasova. Mapping gradient fields of landform migration, Geomorphometry 2015. 23-JUN-15, . : ,

TOTAL: 3

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book
07/31/2015 11.00	Helena Mitasova, Laura Tateosian, Eric Hardin, Margery Overton. GIS-based Analysis of Coastal Lidar Time-Series, New York: SpringerBriefs in Computer Science, (01 2014)

TOTAL: **1**

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Best paper award at Geomorphometry 2015

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Emily Russ	0.10	
Keren Cepero	0.10	
Paul Paris	0.10	
Vaclav Petras	0.50	
Anna Petrasova	0.50	
FTE Equivalent:	**1.30**	
Total Number:	**5**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Michael Starek	0.10
FTE Equivalent:	**0.10**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Helena Mitasova	0.10	
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Emil Russ	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Paul Paris	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Title: **Terrain dynamics analysis using space-time domain hypersurfaces and gradient trajectories derived from time series of 3D point clouds**

Statement of the problem studied

Anthropogenic activity and natural processes modify land surface at various rates and scales, ranging from landscape evolution over geological time scale to changes caused by natural events or human activities that can alter the shape of land surface within few days. Recent research based on lidar data (for example, Burrough and Tebbens 2008, Starek et al. 2009, Zhong and Xie 2009) indicates that short term topographic changes can be highly spatially variable and depending on selection of time intervals, spatial units and spatial and temporal data aggregation methods differing or even quite opposite trends can be derived. Complex spatial and temporal patterns of elevation change have been observed for stream channels (McKean et al. 2009) and for disturbed landscapes exposed to severe erosion (Kincey and Challis 2009). Moreover, natural hazards often involve significant changes in topography induced by coastal or stream channel erosion, aeolian sand trans- port, or gravitation forces on unstable hillslopes. Quantification of these changes, especially their evolution over time, is critical for hazard management and mitigation.

Modern 3D mapping technologies such as lidar are now routinely used to monitor 3D landscape change at high spatial and temporal resolutions. Over the past decade new methods and techniques were developed to analyze these monitoring data and derive quantitative metrics of observed changes. Current analyses of multitemporal lidar data focus on spatially aggregated volume change over time, elevation change between two time snapshots, tracking extracted feature change such as shoreline or channel migration and other spatially or temporally aggregated measures (White and Wang 2003, Mitasova et al. 2004, 2005, Zhou and Xie 2009, Burrough and Tebens 2008). These measures do not fully capture the spatial complexity of elevation surface dynamics, especially acceleration / deceleration that combines elevation (vertical) change with horizontal migration (channel erosion or dune deflation combined with migration, shifting areas of hillslope erosion and deposition).

Over the past decade, short term terrain dynamics research has focused on elevation, volume or feature change for beach-foredune systems in coastal areas (White and Wang 2003, Zhou and Xie 2009, Burroughs and Tebens 2008, Starek et al. 2007, Mitasova et al. 2004, 2005, Sallenger et al. 2003, Stockdon et al. 2002), forest canopy elevation surfaces (Vepacomma et al. 2008) and river channel dynamics (McKean et al. 2009) and erosion of disturbed landscapes (Kincey and Keith, in press). The current approach to analysis involves mapping differences in elevation between two time snapshots, temporal evolution of aggregated volume change, averaged horizontal shoreline change and temporally aggregated statistical measures.

Repeated lidar surveys generate time series of point cloud data at unprecedented spatial and temporal resolutions. For the first time, this new type of 3D data is available as a regional, decadal time series, providing an opportunity for transition from the traditional, static representation of topography to terrain abstraction represented as a 3D dynamic layer. Recently, we have introduced new concepts for temporally aggregated representation of terrain dynamics using time series of high resolution 2D raster maps based on core and envelope surfaces and contour evolution bands (Mitasova et al. 2009). This approach is based on per cell analysis of lidar time series of elevation data that combines high level of spatial detail with summary statistics over time. We have defined a new concept of stable core and envelope surfaces computed as the minimum and maximum elevation at each cell measured over the given time period (Figure 1). These two surfaces define a 3D layer within which the elevation surface evolved (Mitasova et al. 2009a,b) and they can be used to derive contour evolution band for a selected elevation to represent range of its horizontal migration. Additionally, computation of regression for each cell allows us to map distribution of rates and trends of elevation change at high resolutions (Mitasova et al. 2009b).

To fully capture elevation dynamics in a continuous space-time domain we proposed to compute and analyze it as a trivariate function represented by a space-time voxel model. Time series of lidar data include massive point clouds with varied point density and sampling patterns. Heterogeneity in lidar point could data acquired over the past decade is due not only to rapid evolution of lidar mapping technologies, but also due to different objectives of individual surveys. Moreover, there are significant differences in time intervals between the surveys, for example, in coastal regions the time intervals range between few days (pre and post storm surveys) to 2-3 years. Also spatial coverage may not be complete for all surveys, creating additional gaps in the time series. Computation of continuous space-time model of terrain evolution from massive, noisy point data, heterogeneously distributed over space and time is therefore non-trivial.

The objective of this project was to develop a new framework for terrain evolution research using *hypersurface geometry analysis* based on time series of point cloud elevation data and to introduce new terrain dynamics metrics that fully capture spatial and temporal variability as opposed to many currently used approaches that rely on various levels of spatial or temporal aggregation or trace only selected terrain features. The hypersurface geometry provides the foundation for mapping space-time gradient trajectories, stability, acceleration, and breaks in terrain dynamics in order to reveal spatial patterns of trends in terrain evolution. This novel concept also introduces novel approach to visualization of landform evolution. To facilitate investigation of representation and analysis of terrain change and its impact on landscape processes from lidar point data under controlled conditions we proposed to further develope the Tangible Geospatial Modeling System (Mitasova et al. 2006).

Summary of the most important results

Dynamic terrain representation Several approximation methods were investigated and optimized to compute space-time elevation voxel models from time series of lidar point data that represent evolution of a selected type of land surface, such as bare earth. The methods were evaluated and further developed using airborne lidar time series acquired for the North Carolina coast (Hardin et al., 2014, Mitasova et al. 2012, Russ 2013) using more than 14 lidar surveys acquired between 1996-2009 in a region with diverse, highly dynamic topography, rapid development and vegetation expansion. Hierarchy of resolutions was used for the analysis, from 0.3 m to 4m horizontal and quarterly to annual temporal resolutions. The prevailing processes driving topographic change in this area are wind sand transport, wave and storm surge induced beach and dune erosion and human intervention such as beach nourishment and dune reconstruction and stabilization efforts. In addition to the voxel and isosurface based approach, a novel method was proposed for tracking the migration of larger sections of barrier islands. The results or our previous analyses demonstrated that large component of complex spatial patterns of coastal evolution are due to sand redistribution rather than total sand loss or gain. To capture the influence of mass redistribution on coastal landform migration Paris and Mitasova (2014) proposed a technique based on center of mass tracing which, together with the space-time gradient fields provides comprehensive insight into the landform migration and deformation.

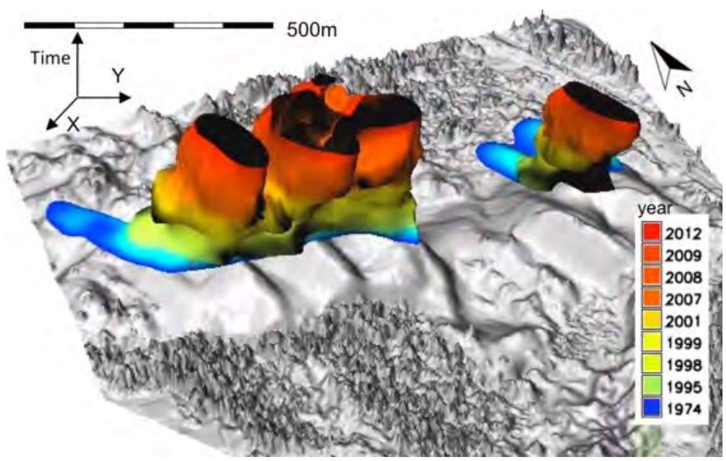


Figure 1 Elevation isosurfaces (evolution of 16m contour) extracted from the space-time elevation voxel model of Jockey's ridge dune between 1974-2012 (Petras et al. 2015, see also animations in the presentation http://fatra.cnr.ncsu.edu/stanalytics2015/#/5).

In addition to the coastal data a time series of eroding bank data were acquired by terrestrial lidar (equipment funded through DURIP ARO program) and the space-time voxel representation was used to analyze the bank evolution and link the geometric properties of its change to the underlying processes. The concept of discrete and continuous space-time cube (STC) was introduced and applied for analysis of coastal and stream bank data (Starek et la., 2013, Figure 2.)

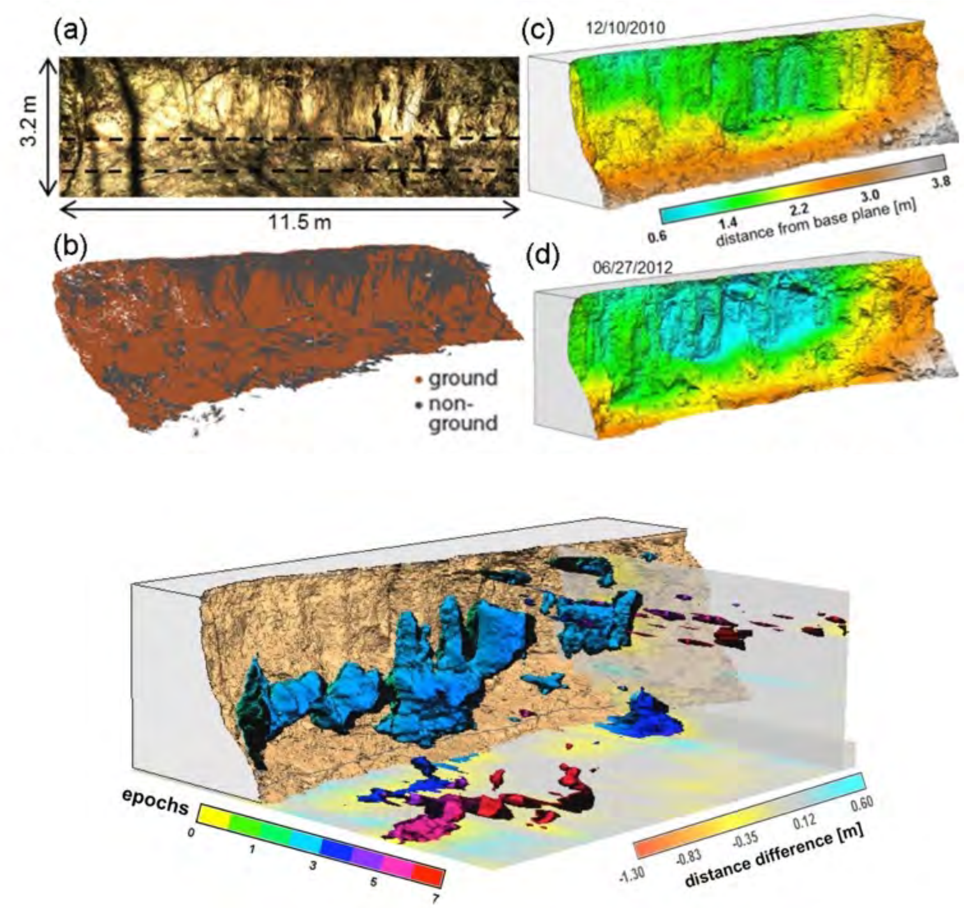


Figure 2. Eroding stream bank : (a) image, (b) point cloud, (c) first and (d) last snapshots. The bottom image shows isosurfaces of change greater than a given threshold extracted from the space-time cube representation.

STC cross-sections and isosurfaces can both aid in visualizing surface evolution as well as reveal connections to the physical processes that underlie the observed change. For example, the contrast between the episodic erosion event that occurred in the post-mill dam section and continuing smaller changes in the older sediments is evident in the isosurfaces of Fig. 2. As observed, there is an abrupt spatially extensive change associated with the 3rd epoch in the post-milldam layer followed by more gradual losses in the two bottom layers over the more recent surveys. This indicates different controlling processes, such as seepage and fluvial erosion. In this way, certain physical processes can generate characteristic isosurface shapes (patterns) of surface evolution. These characteristic patterns can potentially be searched for within a STC of terrain evolution, such as within a classification regime, to detect certain processes underlying observed landform change.

The discrete STC provides a compact representation of the DTM time series derived from the TLS surveys. It is a snapshot representation of surface evolution where the time interval is variable dependent on the survey period. In contrast, the continuous STC enables uniform time intervals through trivariate interpolation. This provides a smoothed (continuous) representation of surface evolution. Furthermore, spatiotemporal gradients (vectors of fastest surface change) can be directly extracted through to further explore the relation between surface evolution and the underlying physical processes.

*Space-time gradients, curvatures D*erivation of equations and numerical methodology for computing models representing components of space-time elevation gradients and specific space time curvatures was fundamental for capturing the properties of elevation surface evolution. The space-time curvatures allowed us to map elevation change acceleration / deceleration in full space-time domain or in specific direction (vertical, horizontal, process-related), as well as identification of stable areas and breaklines in terrain evolution (Petras et al. 2015, Russ 2013).

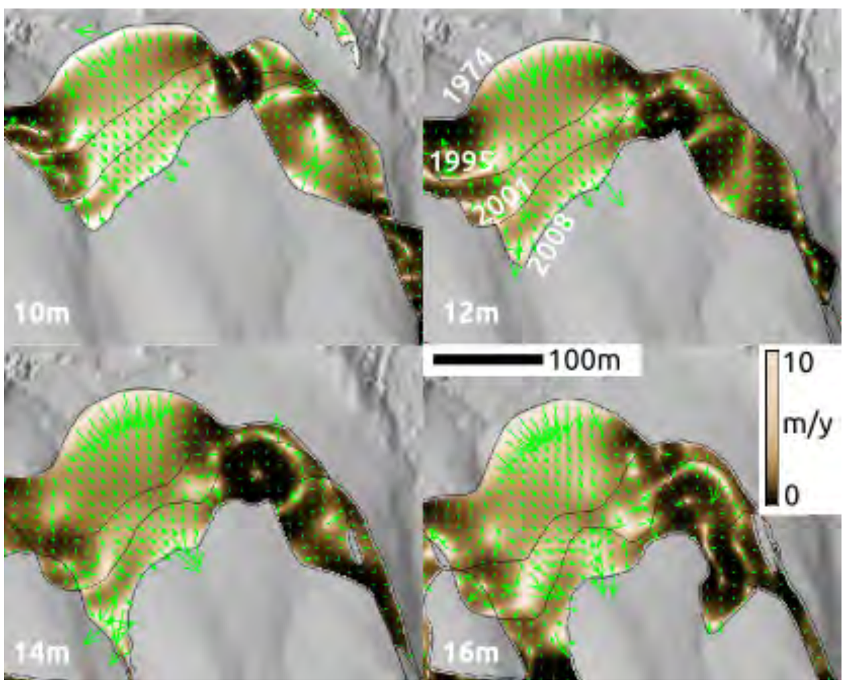


Figure 3 Gradient fields of horizontal migration rates for the windward side of the Jockey's Ridge sand dune system derived at different elevation levels. The complexity of the field increases with elevation and the analysis reveals a rotation pivot point.

We proposed a method for quantifying horizontal migration of complex landforms based on the analysis of contour time series with the aim to generate a quantitative representation of magnitude and direction of landform evolution at any point in space and time. To quantify the rate and direction of contour horizontal migration we segment the time series of contours into non-intersecting segments which is equivalent to segmentation of the isosurface in Fig. 1 into sub-surfaces which can be represented by bivariate functions. Each of these sets of contour segments then define a bivariate function which represents time as a function of contour position.

The time series of contour segments which fulfill the above condition can then be interpolated using a suitable GIS-based interpolation to create a raster representation of the temporal function. This function then allows us to derive a vector field describing the movement of a contour by computing its gradient and its inverse representation. Now we have a two-dimensional vector field which assigns a vector defined by direction and speed v to each position (Figure 3). This vector field represents the rate and direction of landform migration at given elevation. We can derive such a vector field for a set of elevations representing the entire landform and obtain a 3D, spatially variable representation of its horizontal migration and deformation. We can also map locations of migration acceleration and rate of deformation by computing relevant metrics based on second order derivatives (divergence of the vector field or spatio-temporal "profile" curvature). To support the presented concept, we have used and further developed visualization techniques for graphical representation of vector fields using gradient lines, arrow fields, and dynamic comet-like visualization. The raster maps representing migration rates at multiple elevations can also be stacked into a 3D raster (voxel model) and areas of equal migration rates can be extracted and visualized as isosurfaces. The method is general and can be applied to other types of processes, such as fire spread (Figure 4).

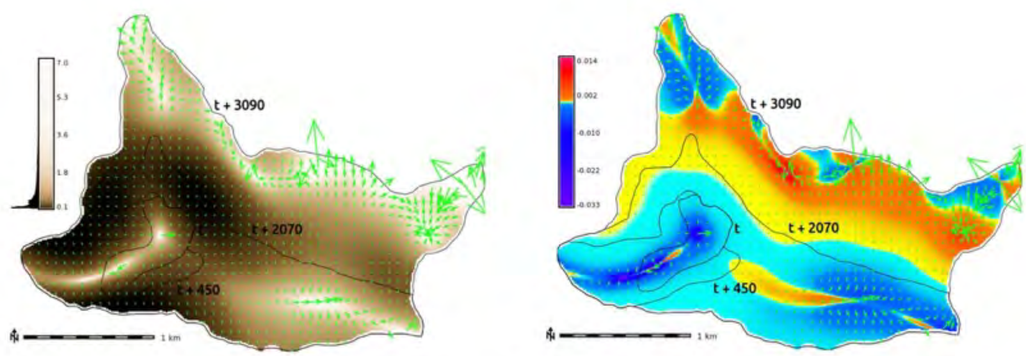
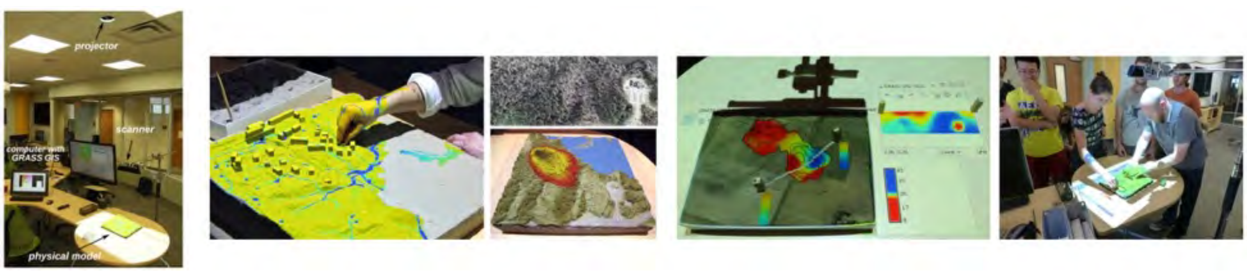


Figure 4. Gradient field of fire spread derived from the observed fire spread isochrones. The color in the right image shows the spread acceleration (orange) and slowdown(blue) derived from the curvatures of the temporal surface.

Tangible Geospatial Modeling Laboratory experiments in controlled environment were be performed using the Tangible Geospatial Modeling System (TanGeoMS) that couples an indoor 3D scanner, projector and a flexible physical 3D model with a standard geospatial modeling system, such as GIS, to create a tangible interface to 3D geospatial data (Figure 3). The flexible scale model can be manually modified to create various landscape configurations by changing the surface geometry, carving-in surface depressions (ponds, stream channels), modifying landforms and changing the roughness of the surface such as adding off road vehicle tracks or a rip-rap. Buildings and other structures can also be added to create anthropogenic environments and simulate interactions between natural processes and human actions. The baseline model is based on real-world data, such as topographic contours derived from bare earth DEMs. The scale model is scanned after each modification, the point cloud is imported into GIS, and a new DEM is computed along with user selected parameters of interest, such as slope, aspect, contours, flow accumulation, and any other parameters available in the GIS. The results are then projected over the model to provide rapid feedback on impacts of introduced terrain changes on topographic parameters and flow patterns. In this project, TanGeoMS was completely redesigned by replacing the 3D laser scanner with Kinect and by replacing plasticine models with polymeric sand. CNC routing and 3D printing was coupled with GIS to provide precise landscape models and molds allowing to us work with accurate DEMs and DSMs. The new system “Tangible Landscape” (Figure 5) was used to generate series of elevation data that represent evolution of topography under controlled conditions to provide test data for the development of spatio-temporal gradient modeling algorithms.



(a) (b) (c) (d) (e)

Figure 5. Tangible Landscape: (a) system setup; (b) simulated surface water flow depth is projected over the model, model is then modified, scanned, and result of new water flow simulation is projected over the surface providing feedback on impact of terrain change on spatial pattern of water flow, model can be further modified by adding buildings; (c) model of a forested area and with dynamic fire spread simulation projected over the model, fire breaks are carved into the polymeric sand surface model and the simulation is re-run to provide feedback on the effectiveness of the proposed firebreak (d) exploration of subsurface soil moisture data represented by voxel model interpolated from soil moisture sensors (e) collaborative exploration of coastal design (see also videos at https://www.youtube.com/channel/UCc37pVh-WE46Xkqeq-KZQsA/videos)

Conclusion

This project introduced a new theory of spatio-temporal morphology that provides a foundation for analysis and modeling of dynamic landscapes using times series of point cloud data. Such analysis is critical to the timely identification and thorough understanding of the physical and informational dimensions of the Battlespace Environment. The developed techniques can improve capabilities to understand the operational environment, aiding in the prediction of changes in mobility capability and timelines in dynamic landscapes due to expected mass movement of earth materials in mobility corridors.

Analysis of terrain dynamics especially quantification of short term acceleration or stabilization can provide fundamental knowledge essential for effective and sustainable management of vulnerable landscapes exposed to high erosion risk.

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Mitasova, H., Hardin, E., Overton, M., and Harmon, R.S., 2009b, New spatial measures of terrain dynamics derived from time series of lidar data, Proc. 17th Int. Conf. Geoinformatics, Fairfax, VA. DOI10.1109/GEOINFORMATICS.2009.5293539

Petras, V., Mitasova, H., Petrasova, A., 2015. Mapping gradient fields of landform migration. In: Jaroslaw, J., Zwolinski, Z., Mitasova, H., Hengl, T. Geomorphometry for Geosciences Bogucki Wydawnictwo Naukowe, Adam Mickiewicz University in Poznan – Institute of Geoecology and Geoinformation. Poznan, Poland. ISBN: 978-83-7986-059-3

Petrasova, A., Harmon, B.,Petras, V., Mitasova, H., 2014. GIS-based environmental modeling with tangible interaction and dynamic visualization. In: Ames, D.P., Quinn, N.W.T., Rizzoli, A.E. (Eds.), Proceedings of the 7th International Congress on Environmental Modelling and Software, June 15-19, San Diego, California, USA.

Paris P., and Mitasova, H., 2014, Barrier Island Dynamics using Mass Center Analysis-A new way to detect and track large-scale change. ISPRS Int. Journal of Geo-Information 3(1), p. 49-65.

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